Stability of *Ficus virens*-Reinforced Slopes Considering Mechanical and/or Hydrological Effects

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Abstract: Vegetation reinforcement for slopes has been recognized as an environment-friendly measure and has been widely adopted in engineering practice. However, the stability analysis of vegetation reinforcement for slopes has mainly been discussed for an infinite slope and common grass and scrub plant species. This study proposes a procedure for analyzing the stability of a finite slope reinforced with *Ficus virens* under transpiration and rainfall conditions. A simplified empirical model for characterizing root cohesion and triaxial testing is utilized to quantify the mechanical effect of roots on rooted soil shear strength. A numerical modeling technique with COMSOL Multiphysics is used to investigate the hydrological effect of roots. The combination of these two effects forms an expression for the unsaturated shear strength of rooted soils. The stability of a vegetated soil slope is then investigated in terms of safety factors and failure mechanisms, with/without considering rainfall. The results show that the stability solutions without consideration of the roots’ mechanical and/or hydrological effects are overly conservative. The hydrological contribution to slope stability could also be partially preserved under short-term rainfall, and as rainfall continues, the hydrological effect is weakened, while the mechanical reinforcement is assumed to be unchanged. In the meantime, the hydrological contribution to slope stability is susceptible to atmospheric conditions, which indicates a favorable effect on water uptake and an adverse consequence for water infiltration.

Keywords: triaxial test; numerical modeling; unsaturated soils; transpiration; rainfall; vegetated slope stability

1. Introduction

Shallow landslides possess the characteristics of high frequency and wide distribution, threatening people’s lives and properties [1,2]. Slope reinforcement is, hence, of crucial significance, particularly in those regions with dense populations and important infrastructure. Apart from widely used engineering measures such as anti-piles, retaining walls, etc., vegetation reinforcement, as a part of soil bioengineering, is deemed environmentally friendly in slope stabilization [3–5]. Different from bare soils, the existence of roots not only provides mechanical reinforcement but also hydrological effects in vegetated soils, as substantiated in the existing literature, e.g., [3,4]. Therefore, engineers are supposed to make use of vegetation reinforcements in slope design, and in-depth research on their mechanism for strengthening slopes and the way to analyze vegetated slope stability aids in putting such a technique scientifically into engineering practice.

The mechanical reinforcement of roots mainly contributes to the tensile strength of a root network, and its effect is to improve the shear strength of a root–soil composite. The tensile strength of different vegetation species has been experimentally investigated, and its magnitude is related to the amount, geometric dimensions, spatial distribution, and even the testing scheme of the roots [6,7]. Based on force equilibrium theory, the shear strength of reinforced soils with consideration of root tensile strength was proposed [8,9].
Another way to quantify a root–soil composite’s shear strength is by performing direct and triaxial shear tests, considering different vegetation species, root amounts, diameters, and distributions [10–15]. Furthermore, some researchers adopted in situ shear testing to study the effects of root characteristics and single or mixed planting on the strength of root-reinforced soils [16,17]. Note that, however, the root length of vegetation species commonly used in slope engineering is usually less than 1 m and even within 0.5 m, which, to a large extent, inhibits the mechanical effects on slope stabilization. Roots’ mechanical effects are supposed to prevent shallow slope failure and surface erosion. For species with well-developed root systems, such as *Ficus virens* trees, their mechanical reinforcement effects are significant, and, hence, pioneering research on this species is conducted in this study.

Roots’ hydrological effects on slope stability mainly affect two aspects: an increase in shear strength via evapotranspiration (transpiration from plants and evaporation from the soil surface) and a decrease in soil permeability by partly occupying pores with live roots [18–23]. Indraratna et al. [18] developed a mathematical model for root water uptake, and the given vegetation species, soil and atmospheric conditions, and pore water pressure distribution were analyzed via numerical modeling within the influencing area of the roots. A comprehensive study by Ng et al. [21] was carried out to quantitatively investigate the reinforcement mechanisms of *Cynodon dactylon* and *Schefflera heptaphylla* and their effects on matric suction, hydraulic conductivity, and slope stability via in situ monitoring, laboratory testing, centrifuge experiments, and theoretical analyses. Such work on atmosphere–plant–soil interactions has extensively promoted the use of soil bioengineering techniques in practice with a more scientific view. Afterward, Ni et al. [24–26] continued to perform in-depth studies on vegetated soil slopes, including planting types and spacing, and a limit equilibrium method was also employed to analyze the stability of infinite slopes. Different from roots’ mechanical reinforcement, a significant effect of hydrological reinforcement lies in the influencing zone exceeding the root zone, which could also preserve a large amount of suction at greater depths under rainfall events [27–29], thereby possessing a higher factor of safety.

The root reinforcement mechanism has mainly been investigated in recent years, with less attention paid to its effects on slope stability. Because of well-known mechanism of root mechanical reinforcement, some calculations of slope stability were performed with consideration of this effect only [30–32]. Note that, however, the slope safety factor ought to be overly underestimated when neglecting the hydrological effects of roots. After having revealed the importance of hydrological reinforcements, e.g., changes in plant-transpiration-induced matric suction and root-induced soil permeability, some researchers attempted to consider this effect in slope stability analyses. It was substantiated that slope stability could be improved to varying degrees, and the factor of safety drops much more slowly for vegetated slopes under rainfall [33,34]. Specific effects are also associated with plant species, soil, and root (plant) properties, as well as external conditions such as (antecedent) rainfall or evapotranspiration. To date, Ni et al.’s study [24] is one of the rare studies investigating the stability of a vegetated soil slope considering both mechanical and hydrological reinforcements. Meanwhile, the stability of rooted soil slopes was also discussed, considering the effects of plant spacing and mixed plant types [35]. However, only an infinite slope was discussed, and, hence, a relevant study on finite soil slopes is necessary for the design of bioengineered slopes, especially for temporary purposes.

In previous studies, focus was placed on the fundamental mechanisms of the mechanical and hydrological effects of plant roots, with less emphasis placed on specific slope stability, especially for finite slopes. Based on this, this paper aims to quantitatively estimate the effects of mechanical and/or hydrological reinforcements on the stability of root-reinforced finite soil slopes under evaporation and rainfall conditions. The soil slope is composed of silty clay, a common material in Chongqing, and reinforced by *Ficus virens* trees, a popular tree species in Chongqing. Triaxial tests were initially performed to determine the shear strength of the root–soil composite. Resorting to the COMSOL Multiphysics
5.6 software (COMSOL, Stockholm, Sweden), the hydrological effects on the pore pressure distribution within unsaturated soil strata were simulated in transient states, and the slope stability under the conditions of evaporation and rainfall was analyzed, considering four different types of root architecture. The safety factor and failure mechanism of a finite vegetated soil slope were investigated, accounting for roots’ mechanical, hydrological, and combined effects, which is the novelty of this study.

2. Roots’ Mechanical Reinforcement

2.1. Simplified Model

Experimental studies demonstrate that a root mechanical reinforcement is highly related to its amount, layout, and tensile strength, and its contribution to the shear strength of vegetated soils is considered to be the so-called root cohesion, $c_r$. Wu et al. [9] initially proposed a semi-empirical formula for characterizing $c_r$ based on the following assumptions: (1) the shear band is sufficiently thick and remains unchanged during shearing; (2) the roots are soft and have a uniform diameter, behaving as a linearly elastic material when stretched along the length direction, crossing and being perpendicular to the shear plane; and (3) the roots’ surface possesses sufficient frictional resistance and constraints with enough anchorage length to prevent pull-out, and all the roots break simultaneously when the tensile stress reaches the tensile strength limit. This model has been extensively applied to evaluate roots’ contribution to cohesion due to its clear concept, simple expression, and ease of application. Subsequently, such a model was modified by Preti and Schwarz [36] and Feng et al. [37]. The modified expression of $c_r$ gives:

$$c_r = k_1 \cdot k_2 \cdot T_r \cdot k_{RAR} \cdot g(z)$$  \hspace{1cm} (1)

where $k_1$ denotes a correction coefficient, reflecting the effects of progressive root breakage on the soil’s shear strength; $k_2$ is another correction coefficient for considering the directions of roots; $T_r$ is the average tensile strength of the roots; $k_{RAR}$ characterizes the root area ratio, defined as the ratio of the total roots’ cross-sectional area to the soil’s cross-sectional area; and $g(z)$ is the function of roots’ distribution and architecture along depth $z$ in the vertical direction. As stated by Preti and Schwarz [36], $k_1$ equals 0.4, and $k_2$ is mathematically expressed by $\sin \alpha + \cos \alpha \cdot \tan \phi'$, which is approximately equal to 1.2 ($\alpha =$ angle of shear distortion at root breakage, and $\phi' =$ internal angle of soil friction). Therefore, the roots’ contribution to cohesion can be readily estimated, provided that the above parameters are known. This modified model is suited to numerical modelling and theoretical analyses of slope stability [38–41].

2.2. Triaxial Testing

Triaxial tests, due to their intrinsic characteristics, have been popularly applied to measure the shear strength of geomaterials, with no exception for vegetated soils. In this study, the tree species *Ficus virens* was selected for reinforcing soil slopes, and such a species is not uncommon to see in Chongqing with the following merits: resistance against wind, air pollution, and barren soils; rapid growth; and being easy to plant and flourish (Figure 1a). A preliminary study focuses on *Ficus virens* seedlings with an average of 2.5 years’ growth for testing. It is observed that there are main straight roots, branched roots, curved roots, lateral roots, and fibrous roots. Comparatively, fibrous roots are short and slender, with many discrepancies in the strength of each root being hard to quantify and hence not considered in the analyses. A single root’s architecture is shown in Figure 1b.

In the preparation of the triaxial samples, the classical silty clay in Chongqing was selected, and its physical properties were tested, as summarized in Table 1. A dry density of 1.65 g/cm$^3$ was measured for the silty clay sample, with a 19% moisture content. In an effort to well account for the roots, a relatively large size of 50 mm $\times$ 100 mm was adopted for ease of sampling. The silty clay was fully rested for 24h at the established water content. The specimens were prepared directly in the trivalvular membrane, in which the roots were arranged according to the designed layout, and each test was repeated at least
twice. The prepared specimens were placed in a saturated cylinder and evacuated for more than 3 h, then filled with water and left overnight, and finally the saturated specimens were mounted in a triaxial cell for testing. Due to the complex root system of *Ficus virens* seedlings, a specific layout with a curved main root and horizontal lateral roots (SH) was designed for simplification. The size of the main (lateral) roots was 80 mm (30 mm) in natural length and 3 mm ± 0.15 mm (2 mm ± 0.1 mm) in average diameter. The same amount of roots (0.01 g/cm²) of 2 g was used in each sample, where the weight of the main root was approximately 0.4 g and that of the lateral roots in each layer was about 0.4 g, for a total of four layers. Rooted soil specimens were prepared in a specific way that was different from the preparation of plain soil: the soil was put into the mold five times and compacted layer by layer; the roots were placed in each layer according to the designed scheme, where the main root needs to be embedded into the soil after the first layer’s compaction; and the tool for compacting was a special solid round bar with a diameter of 20 mm.

![Lateral, main straight, curved and branched roots](image)

**Figure 1.** Illustration of *Ficus virens*: (a) adult trees and (b) single-root architecture of seedlings.

<table>
<thead>
<tr>
<th>Natural Gravity (Kn m⁻³)</th>
<th>Natural Water Content</th>
<th>Maximum Dry Density (g m⁻³)</th>
<th>Optimum Water Content</th>
<th>Plastic Limit</th>
<th>Liquid Limit</th>
<th>Plasticity Index, Ip</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.7</td>
<td>19.36%</td>
<td>1.83</td>
<td>12.35%</td>
<td>15.52%</td>
<td>30.92%</td>
<td>15.4</td>
</tr>
</tbody>
</table>

After having well prepared the samples, a consolidated and undrained test scheme was adopted under confining pressures of 50 kPa, 100 kPa, and 200 kPa. The shearing rate was set to be 0.1 mm/min, and the tests terminated when the axial displacement reached 20 mm. After testing, the failure point was defined as the peak point of the principal stress difference, \((\sigma_1 - \sigma_3)_f\), when there exists a peak stress, or the point of 15% axial strain in the absence of a peak stress.

The triaxial test results are illustrated in Figure 2 for the plain (P) and SH-rooted soils. An obvious strain-hardening behavior is observed in Figure 2a for the plain soil, with an increase in the axial strain, and hence there is no peak value of deviator stress. In contrast, the rooted soils gradually reach a plateau at a relatively high axial strain. It is as expected that the deviator stress is positively related to the confining pressure, demonstrating a higher shear strength at a larger confining pressure or a deeper depth. Besides a higher deviator stress, more excess pore water pressure (PWP) is consequently generated at larger confining pressures, as shown in Figure 2b. During shearing, the excess PWP had rapid growth at relatively small axial strains, followed by a gradual decrease. This phenomenon demonstrates that the soil sample experienced shear contraction initially and then shear dilation. This is also substantiated in the effective stress path in Figure 2c, where the point of a phase transformation from contractive to dilative behavior is quite obvious.
Based on the above test results, Mohr circles are readily plotted, as portrayed in Figure 3. It is found that the Mohr circle of the rooted soil at a confining pressure of 50 kPa (100 kPa) is approximately the same size as plain soil’s at 100 kPa (200 kPa), indicating the significant impact of roots’ mechanical reinforcement on the soil’s strength. A curve fitted with the least-squares method is adopted to approximate the \( K_f \) line, based on which the effective stress parameters cohesion, \( c' \), and friction angle, \( \phi' \), are obtained for the plain and vegetated soils. It is expected that the roots’ mechanical contribution to soil cohesion is to some extent significant, with its value increasing from 3.6 kPa to 20.5 kPa. Nonetheless, the variation in the soil friction angle modified by the roots can be neglected. This further demonstrates that the simplified model in Section 2.1 is valid for considering root cohesion only when studying the roots’ mechanical reinforcement.

![Triaxial test results](image)

**Figure 2.** Triaxial test results for six specimens under confining pressure of 50, 100, and 200 kPa: (a) stress–strain response, (b) excess PWP, and (c) stress path in \( q-p' \) space.

**Figure 3.** Mohr circles and strength parameters of plain and rooted soils.

### 3. Hydrological Model of Rooted Soils

Natural soils reinforced by vegetation are usually unsaturated, which means that the soil slope response is highly influenced by atmospheric conditions such as rainfall, temperature, and underground water. In the realm of unsaturated soils, Richard’s equation [42], derived from the mass conservation law and Darcy’s law, is crucial in estimating water flow and pore water pressure, especially in transient states. The introduction of roots to unsaturated soils makes the issue more complicated because of the hydrological effect, which highly affects water retention and holding capacity. Different from the traditional model in unsaturated soils, a sink term, \( S(z) \), varying with depth, \( z \) (elevation), is introduced to account for the water absorption effect by the root system. As a consequence, the modified Richard’s equation is used instead herein, and its expression gives

\[
\frac{\partial}{\partial x} \left( k_x(\theta) \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial z} \left( k_z(\theta) \frac{\partial H}{\partial z} \right) - S(z) = C(\theta) \frac{\partial (H - z)}{\partial t}
\]  

(2)
where $H$ = the total head; $k_x(\theta)$ and $k_z(\theta)$ = the hydraulic conductivity in the $x$ and $z$ directions; $S(z)$ = the sink term, representing the root water uptake; $\theta$ = the volumetric water content; $t$ = time; and $C(\theta)$ = the specific water capacity. Based on the theorem that water absorption is influenced by the soil–water potential in the root zone, Feddes et al. [43] proposed an empirical model for root water uptake, i.e.,

$$S(\psi, z) = \alpha(\psi)T_p$$

(3)

in which $\alpha(\psi)$ = a dimensionless transpiration reduction function which is directly associated with the matric suction, $\psi$, whose value varies from 0 to 1, and $T_p$ = the maximal transpiration rate in m/s. Note that this model is suited to a uniform root distribution, and in order to account for the non-uniform distributions of root transpiration rates throughout the whole root zone, a function characterizing the root architecture, $g(z)$, varying with depth, $z$, is introduced to Equation (3), giving

$$S(\psi, z) = \alpha(\psi)g(z)T_p$$

(4)

In this study, the transpiration reduction function proposed by Garg et al. [44] is used, and the specific expression is

$$\alpha(\psi) = \begin{cases} 0.117\ln(\psi)+0.538 & (\psi \leq 52 \text{ kPa}) \\ 1 & (52 \text{ kPa} < \psi \leq 90 \text{ kPa}) \\ -0.335\ln(\psi)+2.6 & (90 \text{ kPa} < \psi \leq 1500 \text{ kPa}) \end{cases}$$

(5)

Prior to solving Equation (2), the hydraulic conductivity and specific water capacity are supposed to be obtained. Based on the soil–water characteristic curve (SWCC) and capillary model developed by Mualem [45], Van Genuchten [46] derived a closed-form solution for the hydraulic conductivity of unsaturated soils. The corresponding results are written below

$$Se = \frac{1}{1 + |\alpha H_p|^n}$$

(6)

$$\theta = \theta_r + Se(\theta_s - \theta_r)$$

(7)

$$C(\theta) = \alpha(n - 1)/(\theta_s - \theta_r)Se^{1/m}(1 - Se^{1/n})^m$$

(8)

$$k(\theta) = k_sSe^{\frac{1}{2}}[1 - (1 - Se^{\frac{1}{n}})^m]^2$$

(9)

in which $n$, $m$, and $\alpha$ = empirical coefficients with $m = 1 - 1/n$; $H_p$ = the pressure head; $\theta_r$ = the residual volumetric water content; $\theta_s$ = the saturated volumetric water content; and $Se$ = the effective degree of saturation. The experimental data substantiate that such a VG model is suited to many kinds of soils.

Based on the Galerkin principle of the weighted residual, the above seepage equation can be further expressed in a matrix equation, and a specific method for solving this equation can be found in Zhou and Qin [47].

4. Stability Analyses of Rooted Soil Slopes

4.1. Root Architecture

In the preceding sections, it is found that both the mechanical and hydrological reinforcements of roots are greatly affected by the root architecture. A uniform root architecture is assumed for the simplified model in Equation (1), and in triaxial testing, a specific root arrangement (SH) was made. Assumptions are also made when considering the hydrological effects of live roots, and this can be found from the model in Equation (4), where the function $g(z)$ is used to characterize the root architecture effect.
Note that, however, the root system is quite complex, and hence it is rather challenging to precisely quantify the root architecture. Resorting to the analysis software of root images provides a sound avenue to quantitatively characterize the roots’ geometrical properties and hence is suggested to be implemented into sophisticated numerical modelling. For ease of simplification, the root architecture is categorized into four commonly used types: uniform [43], triangular [48], parabolic [49], and exponential [50] distributions. Assuming the same biomass, the $g(z)$ function can be ideally written as

$$g(z) = \begin{cases} \frac{1}{z_r} & \text{Uniform} \\ \frac{2}{z_r} \left( \frac{z - z_{\text{max}}}{z_r} + 1 \right) & \text{Triangular} \\ \frac{2}{z_r} \left( z + z_r - z_{\text{max}} \right) z_r - \left( z + z_r - z_{\text{max}} \right)^2 & \text{Parabolic} \\ \frac{2}{z_r} \left( \exp(z + z_r - z_{\text{max}}) - 1 \right) & \text{Exponential} \end{cases} \quad (10)$$

where $z_r$ = the root depth, and $z_{\text{max}}$ = the elevation of the root top. For ease of illustration, these four distribution types are plotted in Figure 4. In the following analysis, the above four types can be directly used for discussion on mechanical and hydrological effects when it is not convenient to perform corresponding triaxial tests.

![Figure 4](image1.png)

**Figure 4.** Four patterns of root architecture and their idealized representations ($z_r$ = 1.0 m).

### 4.2. Slope Model and Analysis

For a root-reinforced soil slope with its geometrical and boundary conditions shown in Figure 5, the groundwater level is beneath the slope toe elevation, and the sloping surface is subjected to evaporation or rainfall. The upper layer represents the root zone, in which a finer mesh is necessitated in numerical modelling. A total of 12,584 triangular elements are generated. Resorting to COMSOL Multiphysics software, a coupled seepage–stress finite element analysis is carried out in this study.

![Figure 5](image2.png)

**Figure 5.** Slope model with its geometry, boundary conditions, and meshing.
In an unsaturated soil slope stability analysis, including vegetated soil slopes, the presence of air voids makes the problem complicated, which straightforwardly affects the soil stress state together with the pore water pressure. When adopting Terzaghi’s effective stress function to describe the interaction between unsaturated soil particles, it was modified by Bishop and Blight \[51]\ as

\[
\sigma' = (\sigma - u_a) + \chi(u_a - u_w)
\]

(11)
in which \(\sigma'\) = the effective stress; \(\sigma_n\) = the total normal stress; \(u_a\) = the pore air pressure; \(u_w\) = the pore water pressure; and \(\chi\) = a coefficient varying from 0 to 1 to reflect the degree of saturation. For instance, the extreme case of \(\chi = 0\) indicates that all pores are occupied by air, and \(\chi = 1\) indicates a fully saturated state. The difference of \(u_a - u_w\) is termed the matric suction (\(\psi\) used in the preceding section).

On the basis of the effective stress principle and the Mohr–Coulomb failure criterion, Fredlund et al. \[52]\ proposed an equation for unsaturated soil shear strength. When soils are mechanically reinforced by roots, the cohesion contributed by vegetation is supposed to be considered in the equation, which is therefore modified as

\[
\tau = c' + c_r + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi_b
\]

(12)
where \(\phi_b\) = the friction angle with respect to changes in the matric suction.

It has been widely acknowledged that two stress state variables, \((\sigma_n - u_a)\) and \((u_a - u_w)\), could better describe the behavior of unsaturated soils. Due to the intrinsic physical properties of unsaturated soils, the SWCC, Vanapalli et al. \[53]\ further modified the above shear strength equation as

\[
\tau = c' + c_r + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\left(\frac{\theta - \theta_s}{\theta_r - \theta_s}\right)\tan\phi
\]

(13)

As for Equation (13), it is worthwhile pointing out that roots’ mechanical and hydrologic reinforcements are both considered, with the second term on the right-hand side representing the mechanical contribution and the last term considering hydrological effects. When triaxial tests are adopted to measure the shear strength of a root–soil composite, the estimated cohesion is contributed by roots and soil together, which should be \(c' + c_r\) in Equation (13).

After having determined the shear strength parameters of the unsaturated soils, the root–soil slope stability is then estimated by virtue of the strength reduction technique. This is achieved in COMSOL Multiphysics, and specific results are discussed below.

5. Results and Discussion

In the following simulations, the default input parameters are slope angle = 30\(^\circ\); slope height, \(H = 5\) m; groundwater level, \(H_w = 2.5\) m; \(c' = 3.6\) kPa; \(\phi' = 27.3\(^\circ\); root depth, \(z_r = 1\) m; \(T_p = 10\) mm/d; \(k_{RAR} = 0.03\%\); \(T_r = 50\) MPa; \(k_i = 1.516 \times 10^{-6}\) m/s; \(\theta_s = 0.469\); \(\theta_r = 0.106\); \(\alpha = 1.06\) m\(^{-1}\); \(n = 1.395\); and rainfall intensity, \(q = 2.5\) mm/h. Based on these, the pore water pressure in transient states and stability solutions are simulated.

5.1. Pore Water Pressure

In unsaturated soil mechanics, the determination of the (negative) pore water pressure (PWP) is a key and fundamental issue. For one-dimensional steady seepage such as under evaporation or infiltration, analytical solutions for the matric suction (negative PWP) and the effective degree of saturation were derived in closed form \[54]\.

For considering the hydrological effects of vegetated soils, PWP distributions along depth are suggested to be obtained in a numerical manner. Figure 6a shows the effects of different root architectures on the matric suction under transpiration conditions, and it is found that the influence zone of root water uptake exceeds the root length. Provided that the root biomass is the same, the
exponential and triangular roots have a much more significant effect on the improvement in the matric suction, particularly near the ground surface, owing to their larger root densities and hence higher transpiration rates. Comparatively, uniform and parabolic root patterns induce much less-negative PWP’s, and the maximum suction appears at around half the root depth. Overall, the previous two kinds of architecture outperform the latter two in the improvement in the soil suction. Moreover, the PWP distributions are similar to those obtained in the existing literature and, more importantly, are directly related to the root architecture, as presented in Figure 4. Taking a uniform root as an example, the PWP variations against the transpiration time and depth are illustrated in Figure 6b. Initially, it reflects a steady state, and the PWP follows a hydrostatic line. As time goes by, the PWP curve gradually deviates outwards to induce higher matric suction by root water uptake. Its magnitude changes nonlinearly and becomes gradually significant with time. This demonstrates that unsaturated soils tend to have larger shear strengths in a transpiration state based on the extended MC failure criterion.

Rainfall is not uncommon and usually presents periodic characteristics in a specific region. When a vegetated slope is subjected to rainfall, the initial condition right before the start of rainfall is supposed to be determined as a prerequisite, which would directly affect the response of the PWP and slope stability solutions. For example, the PWP at the ground surface is negative 120 kPa for a soil slope reinforced by uniform roots (denoted as U), as shown in Figure 6 and the \( t = 0 \) line in Figure 7a. In contrast, it is only 51 kPa for a bare slope (denoted as B). Afterwards, rainfall starts and it is within expectation that PWP drops significantly in shallow depths. Because of rainfall infiltration, the suction drops to zero instantly near the ground, regardless of bare or rooted slopes. Although the difference between the PWP values is not very varied at those depths where air voids are mainly occupied by rainfall water, it is still a little bit larger for a vegetated slope. However, a much larger suction (negative PWP) is preserved in those depths that water does not reach. Moreover, at a certain depth, rooted soils have a higher suction value in contrast to the bare soil, which is mainly attributed to the lower permeability of the root–soil composite, even during rainfall. This is definitely suited to the case when rainfall time is not long enough; otherwise, all pores would be filled with water, and in this case, it becomes a fully saturated soil slope in which the hydrological effects of vegetation ought to be neglected. The same phenomenon can be observed from the PWP evolution along the section A-A on the sloping surface, which is 1.83 m away from point c in the horizontal direction in Figure 5, where the PWP at depths of 0, 0.5 \( z_r \), \( z_r \), and 2 \( z_r \) (corresponding to a, b, c, and d) is simulated under a total of 72 h of transpiration and thereafter 120 h of rainfall. For ease of illustration, the PWP contours for the bare and vegetated soil slopes are also presented in Figure 8 under rainfall conditions. Intuitively, the suction for the vegetated soil slope is more retained after 24 h rainfall in contrast to the base slope. After a long period of rainfall, for example, 120 h,
one can observe that the contours become similar, with not many discrepancies between the two. This demonstrates that the hydrological effect of roots gradually weakens with rainfall infiltration, which was also substantiated by Ng et al. [55] and Feng et al. [56], who investigated an infinite slope.

Figure 7. PWP distributions for vegetated soils under rainfall conditions: (a) bare vs. uniformly rooted soil slope and (b) along section A-A of the sloping surface.

Figure 8. PWP contours for bare and rooted soil slopes against rainfall time. (Note: B represents bare slope, and U represents vegetated slope with uniformly distributed roots).

5.2. Stability Results

A straightforward way to evaluate slope stability is by means of a safety factor, which can be computed by the strength reduction technique. In this part, roots with a uniform architecture are taken as an example for slope stability analyses. The hydrological effects of such a slope were investigated in the previous part, which is directly adopted for further analysis herein. As for the mechanical reinforcement of roots, the shear strength of the root–soil composite was taken without distinguishing the root cohesion. The root layout in triaxial testing, to some extent, can be considered a uniform architecture. Nonetheless, the so-called root cohesion determined by root properties is adopted in the latter parametric studies for ease of simplification.

Based on the shear strength and hydrological parameters, the factor of safety (FoS) for the rooted soil slope is 2.320 after 72 h of plant transpiration, and it is 2.162 for the
bare slope. This indicates that vegetation could improve slope stability, and the degree of improvement is determined by its properties. The corresponding plastic strain contours are shown in Figure 9a,b. The plastic shear band (or critical slip surface) shows that a relatively deep failure mode is induced at the limit state in the presence of roots. This is due to the additional resistance stemming from the roots’ mechanical and hydrological reinforcements, thereby requiring deeper soils to be mobilized to reach the limit equilibrium state. Nonetheless, the slope stability is significantly weakened under rainfall infiltration. For instance, the factor of safety drops to 1.477 for the bare slope and 1.639 for the rooted soil slope after 120 h of rainfall. In this case, the higher FoS is predominantly attributed to the mechanical reinforcement of the roots, and the hydrological effect is minimal because plant transpiration ceases and only a certain amount of suction is preserved, which can be seen in Figure 8. Correspondingly, the plastic shear strain is also obtained, as illustrated in Figure 9c,d. It is shown that a much shallower failure mechanism results from rainfall, although a relatively deep slip surface can also be observed for the vegetated slope. In other words, the use of vegetation is capable of preventing shallow slope failure under rainfall because the plant species used in practice usually do not have long roots. Moreover, this has also been proven to be valid for the prevention of scouring and erosion.

![Image](attachment:Fig9.png)

**Figure 9.** Plastic shear strain contours: (a) bare slope without rainfall, (b) vegetated slope without rainfall, (c) bare slope with rainfall, and (d) vegetated slope with rainfall.

It has been widely acknowledged that vegetation could improve slope stability through its mechanical and hydrological reinforcement mechanisms. In an effort to investigate these two effects on slope stability, the single or combined contribution to the factor of safety is discussed herein, and the results are presented in Figure 10 with/without considering rainfall. Following the preceding analysis, where rainfall starts at \( t = 0 \), it is as expected that rainfall infiltration results in a sharp decrease in the FoS. Initially, the contribution of the hydrological reinforcement (UH) to the FoS is larger than that of the mechanical effect (UM). However, the FoS computed from the UH experiences a gradual downward trend when rainfall starts for a short time, for example, less than 40 h here, owing to a small amount of water infiltrating into upper soils, and hence a certain amount of matric suction is still preserved. Afterwards, the UH effect is greatly undermined with an increasing amount of water infiltration. At \( t = 120 \) h, the FoS from the UH approaches that of the bare slope, and if rainfall continues for enough time, the same FoS would be obtained. In other words, the FoS curve from the UH gradually approaches that of the bare slope, and the curve from the UM would be close to that obtained considering the combined effects (UH + UM) during persistent rainfall. This indicates that the roots’ reinforcement contribution to the improvement in slope stability is principally contributed to by the mechanical effect. When
rainfall lasts for 120 h and then suddenly stops, one can find that an obvious increase in the FoS is induced. This is sensible since, in this case, vegetation starts to transpire and water is gradually taken up by the roots. As time goes by under plant transpiration, the hydrological effect becomes significant and gradually exceeds the mechanical contribution. It is worth pointing out that the mechanical reinforcement is assumed to not be affected by atmospheric conditions, which only influence the hydrological effect. Therefore, the FoS value, considering a single reinforcement effect (UH or UM), ought to be no less than that of the bare slope and no more than that obtained with considerations of the coupled hydro-mechanical effects, demonstrating the reinforcement contribution of roots for improving slope stability. Without considering these effects, the obtained results are deemed conservative. In specific engineering practices, the use of vegetation could bring about economical effects or be considered redundant for slope stability.

In order to investigate the effects of relevant parameters on the rooted slope stability, a parametric study is carried out herein without considering rainfall, and the results are shown in Figure 11. As expected, an increase in the root depth and tensile strength results in a linearly increased factor of safety. This stems from the additional root cohesion, as defined in Equation (1). This implies that a plant with long roots is favorable for improving slope stability, and hence, in the case of mature *Ficus virens* trees with rich root systems, it could play a significant role in maintaining slope stability. Meanwhile, the higher the transpiration rate, the more root water uptake, and therefore there is a higher factor of safety for the rooted soil slope. Again, for the tree species *Ficus virens*, which is usually leafy and has a strong trunk, as can be seen in Figure 1a, a large amount of water is continuously transferred from soils due to its high transpiration, and hence it is common to see a well-reinforced slope, even at 90°. As for the slope geometry, such as the slope angle and height, it is observed that the factor of safety is inversely proportional to these two parameters. Interestingly, the hydrological effect of roots becomes gradually weakened, and in turn, the mechanical reinforcement is considered to be predominant, especially with an increase in slope height. It is again substantiated that an estimation of slope stability without considering coupled hydro-mechanical effects or even any single effect is deemed conservative. In this case, it is costly to prevent slope failure and landslides in practice.

![Figure 10. Effects of mechanical and/or hydrological reinforcements on the factor of safety. (Note: B represents bare slope, UH represents vegetated slope with uniformly distributed roots considering hydrological effect, and UM represents vegetated slope with uniformly distributed roots considering mechanical effect).](image-url)
Figure 11. Effects of root properties and slope geometry on the FoS.

6. Conclusions

The stability of a vegetated soil slope with/without considering rainfall is investigated in this study, in combination with triaxial testing and numerical modelling. Taking the tree species *Ficus virens*, which widely existed in Chongqing, as an example, triaxial tests were initially performed to determine the shear strength of the root–soil composite. Another way of quantifying the mechanical reinforcement of roots is by means of the root–soil cohesion model. Roots’ hydrological effect is quantified by virtue of COMSOL Multiphysics in terms of the PWP (matric suction). Prior to the stability analyses, the unsaturated shear strength model of the rooted soils is developed with consideration of the hydro-mechanical effects. The factor of safety and plastic shear strain in the critical state are simulated for a vegetated soil slope under different scenarios. Some key findings are presented as below:

1. *Ficus virens* roots contribute to an increase in the effective cohesion of the root–soil composite, more than 10 kPa, while they do not have much influence on the effective friction angle.

2. Matric suction in unsaturated soils is proven to be highly associated with root architecture, and an exponential root distribution tends to have more obvious hydrological effects within its influencing zone.

3. The hydrological contribution to slope stability is greatly influenced by climate change. In a short period of rainfall, the factor of safety considering the hydrological effect alone is higher than that of a bare slope. However, this effect gradually weakens until it disappears.

4. Rainfall infiltration tends to induce a shallow failure mechanism, and hence, vegetation in practice could work well for the prevention of shallow slope failure.

5. A conservative outcome is yielded when not considering the hydro-mechanical or even the single reinforcement effect of roots, which is uneconomical in slope design, especially in this era of minimizing carbon emissions.

6. A soil slope is suggested to be environmentally reinforced by species with a large tensile strength and root area ratio and a leafy superstructure with a high capability
of transpiration, aiming to provide more mechanical and hydrological reinforcements for slope stabilization.

This study provides a relatively comprehensive procedure for the stability analysis of a vegetated soil slope, from testing to numerical simulations. Note that a uniformly distributed root system is mainly discussed in this study, which is usually not the case in engineering practice. More studies on considerations of complex root architectures are to be carried out in future research. Meanwhile, it has been found that the roots of Ficus virens are, to some extent, arbitrary; a reliability analysis [57] is preferred, and the load transfer mechanism [58] can be further investigated. Soil variability also widely exists in site, and in this case, in-depth research on the effects of soil variability and strength properties on slope stability [59–61] is necessary and will be performed in future.

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